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The Influence of Glazing Selection on Commercial Building Energy Performance in Hot and Humid Climates

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THE INFLUENCE OF GLAZING SELECTION ON COMMERCIAL BUILDING ENERGY PERFORMANCE IN HOT AND HUMID CLIMATES

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THE INFLUENCE OF GLAZING SELECTION ON COMMERCIAL BUILDING ENERGY PERFORMANCE IN HOT AND HUMID CLIMATES

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ABSTRACT

This paper presents a comparative study in which commercial building perimeter zone electric energy (cooling, lighting, fan) and peak electric demand are analyzed as a function of window glazing type, with a particular emphasis on the use of glazings with wavelength-selective solar-optical properties. The DOE-2 energy analysis simulation program was used to generate a data base of the electric energy requirements of a prototypical office building module located in Singapore. Algebraic expressions derived by multiple regression techniques permitted a direct comparison of those parameters that characterize window performance in hot and humid climates: orientation, size, and solar-optical properties. Also investigated were the effects of exterior and interior shading devices, as well as interior illuminance level, power density, and lighting controls to permit the use of daylighting. These regression equations were used to compare the energy implications of conventional window designs and newer designs in which the type of coating and substrate were varied. The analysis shows the potential for substantial savings through combined solar load control and lighting energy use reduction with daylighting.

INTRODUCTION

The impact of nonresidential building design on energy conservation in hot and humid climates was the major topic at the ASEAN Conference on Energy Conservation in Buildings (USAID 1984), Singapore. Window and daylighting technologies were widely discussed because fenestration has proven to be the most significant envelope design factor affecting energy use in nonresidential buildings. In Singapore, and other hot and humid locations, exterior shading and window size have been successfully used to limit solar heat gain. Lately, architects and engineers have been designing buildings with large areas of glass and without exterior shading. Tinted glazing is being specified to reduce solar loads and comply with energy codes.

The benefits of using daylighted perimeter zones in office buildings were also discussed at the ASEAN conference. A large fraction of electric lighting can be saved by dimming or switching electric lights in response to available daylight. The degree to which daylighting can reduce lighting loads depends primarily on the size and visible transmittance of the window. Other studies (Arasteh 1985; Johnson 1986; and Sweitzer 1987) have demonstrated the total energy-related benefits of daylighting building perimeter zones.

While daylighting energy savings from windows are a function of window area and visible transmittance, cooling loads from windows are a function of area and shading coefficient. Previous studies, referenced above, have explored the critical relationship between solar transmittance and daylighting benefits if energy performance is to be optimized. From an energy viewpoint, the ideal glazing would have a high visible transmittance, τ_v, and a low shading coefficient, SC. We define a glazing luminous efficacy constant, k_e, the ratio of τ_v to SC, as a relative indicator of glazing performance in this regard. Conventional blue and green glazings have higher k_es than other tinted, reflective, or clear glazings since they transmit comparatively higher fractions of visible solar radiation than solar infrared radiation. Low-E coated glazings, introduced in recent years to reduce glazing conductances and suppress heat losses, also have the property of admitting a higher proportion of visible light relative to the total solar transmittance, thus making them attractive candidates for application in cooling dominated climates.

The energy implications of using glazings with different areas, SCs, τ_vs, and k_es are a function of climate, orientation, and building operating characteristics. In this paper, we discuss these effects in the context of the Singapore climate. We compare the performance of seven different glazing types and demonstrate the viability of new glazing technologies to reduce electric energy consumption and peak electrical demand in a hot and humid climate.

METHODOLOGY

The procedure used in the study involved the use of multiple regression equations that defined the electric energy and peak electric demand of a prototypical single-story office building module. These equations were derived from a large number of DOE-2 (Building Energy Simulation Group 1984 and Winkelmann 1986) hour-by-hour simulations that were completed for a variety of configurations using 1979 weather data for Singapore (1.3 °N latitude). On an average day in Singapore, the dry bulb temperature varies between 25 °C (76 °F) and 30 °C (85 °F) and the relative humidity between 74 and 88 percent. Sunshine hours are limited to 30 to 48 percent of the possible hours because of cloud cover that is prevalent during most of the year. The module shown in Figure 1 has four perimeter zones consisting of ten offices, each 4.57 m (15 ft) deep by 3.05 m (10 ft) wide, surrounding a central core zone of 929 m^2 (10,000 ft^2) floor area. Floor-to-ceiling height was 2.6 m (8.5 ft) with a plenum of 1.07 m (3.5 ft) height. Work presented at the ASEAN conference (USAID 1984) also used this module in tabulating daylighting characteristics.

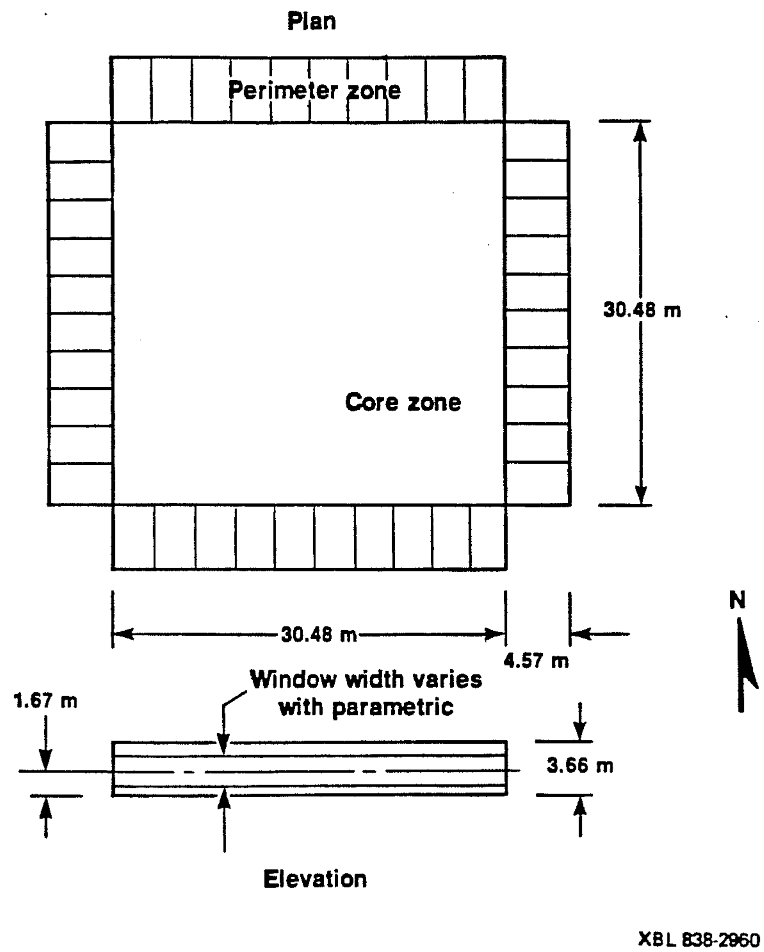

Figure 1. Plan of simulated office building showing alternative window-to-wall ratios. Module consists of a 929-m^2 core surrounded by 4.57-m-deep perimeter zones, each divided into 10 modules 3.05 m wide.

A paper by Johnson (1983) contains more detailed information on the model.

Continuous-strip windows with no setback were used in the exterior wall of each perimeter zone. Thermal transfers were selectively constrained in order to isolate the energy effects of interest, i.e., the floor and ceiling as well as the walls at each end of the perimeter zones were modeled as adiabatic (i.e., no heat transfer) surfaces. The envelope effects can thus be considered analogous to those in an individual office in a series of contiguous offices. Normal building thermal interactions included heat capacity effects and small convective/conductive transfers between core and perimeter.

A data base of electric energy usage and peak electric demand was generated for changing window and lighting system properties. We calculated system extraction rates for each perimeter zone using a single zone constant volume variable temperature HVAC system. Cooling energy was determined by assuming a fixed COP of 3.0. Daytime operational hours were from 7am to 6pm weekdays. Cooling thermostat setpoint was 25.5°C (78°F). The design supply air flow rate per square meter of floor area was 0.031 $l/s\text{-}m^2$ (0.7 cfm/ft^2). Minimum amount of outside air per zone occupant was 2.36 l/s (5 cfm). The economizer limit temperature was 16.67°C (62 °F). Air-infiltration was fixed at an equivalent value of 0.6 airchanges per hour. Our analysis is presented as a function of orientation. Coincident peak loads for the building module were not analyzed; rather, we studied each zone's peak independent of other zones. Sensitivity studies completed prior to this work indicate that other HVAC systems will have a small effect on the numerical results.

The glazing characteristics that were varied included solar optical and thermal conductance properties and area. Lighting characteristics investigated included the use of daylighting with continuous dimming controls for varying lighting power densities and lighting levels. External shading was also simulated with continuous, fixed, horizontally projecting, opaque overhangs. Overhang projection width was varied parametrically to a maximum ratio of projection width to window height of 0.6. Shading by adjacent buildings was not considered in the analysis. Interior shading was simulated using shading coefficient and visible transmittance multipliers of 0.6 and 0.35, respectively. These conventional shades were deployed automatically when transmitted direct solar radiation exceeded 63 W/m^2 (20 W/ft^2). Exterior and interior shading were not simulated simultaneously.

A regression analysis was performed on the DOE-2-generated data base, deriving simplified algebraic expressions that accurately reproduced the simulated electric energy and peak demand. Multiple regression is an analytical technique for determining the best mathematical fit for a dependent variable as a function of many independent variables. The resultant regression expression used to predict these quantities was of the form:

$$\Delta E = \beta_1 \cdot U_g \cdot A_g + \beta_2 \cdot k_o \cdot SC_g \cdot A_g + \beta_3 \cdot k_d \cdot L \cdot A_f \qquad (1)$$

where ΔE is the incremental effect due to the fenestration system. The regression coefficients are denoted by β and the equation has three components chosen to contain the energy effects from a particular building thermal component: conduction (U_gA_g), solar radiation ($k_oSC_gA_g$), and lighting (k_dLA_f), where U_g is the overall conductance of the glazing, SC_g is the shading coefficient, k_o

is a solar correction factor due to overhangs, L is the lighting installed power density, and k_d is a lighting correction term due to daylighting. A_g and A_f are glass and floor areas respectively. Shade management effects are accounted for by revised solar radiation coefficients, β_2.

The regression coefficients are presented in Table 1 for each orientation along with the r^2 values to indicate the goodness of fit of the expression to the data (an r^2 value of 1.0 represents a perfect fit). The configuration parameters are expressed in SI units, i.e., U_g ($W/m^2 \cdot °C$), A_g (m^2), L (W/m^2), A_f (m^2). An analysis of the regression terms shows that they are reasonably physically consistent with expected performance. For example, the β_3 coefficient is almost constant for all orientations since, in the absence of lighting controls, lighting energy is not affected by external conditions. Also, glazing conductance variations are quite small and can be safely ignored because of the much larger contributions from solar gain and lighting. β_2 coefficients for shade management are presented for east and western orientations, only. The shades were not implemented very often in north and south because the direct solar radiation did not approach the level sufficient for triggering the devices. The diffuse component represents a significant portion of available sunlight in these directions.

Tables 2 and 3 show the regression coefficients for the solar and lighting correction terms, k_o and k_d. The solar factor from overhangs was a function of the ratio of overhang projection width to window height (R). Two forms are used to show the effects of overhangs: an exponential to predict electric energy usage for all orientations and both exponential (north and south) and linear (west and east) forms for peak demand predictions.

$$k_o = 1.0 - \delta_1[1 - e^{\delta_2 R}] \quad \text{or} \quad k_o = 1.0 - \delta_1 R \tag{2}$$

where δ denotes the regression coefficients.

The lighting correction factor due to daylighting was also exponential and a function of desired lighting level (C) in lux, and effective aperture (A_e), which is the product of window-to-wall ratio and visible transmittance, i.e.:

$$k_d = 1.0 - [\phi_1 + \phi_2(C)][1 - e^{(\phi_3 + \phi_4 C) A_e}] \tag{3}$$

where ϕ denotes the regression coefficients, which are shown for four orientations in Table 3. North and south are so similar that they can be considered the same.

It was not possible to perform a regression on the DOE-2 simulation results that used shade management because only a limited set of runs was completed; however, changes that occur in the lighting correction factor when shade management is employed are discussed below.

TABLE 1

Regression Coefficients: Annual electricity usage (kWh) and peak electric demand (SI units)

		Electricity		Peak Demand	
		w/o SM	w/ SM	w/o SM	w/ SM
β_1	N	2.387		3.733	
	S	3.104		4.494	
	E	-2.069		.439	
	W	-5.411		.409	
β_2	N	306.114		132.180	
	S	319.910		141.214	
	E	514.862	360.403	237.690	144.991
	W	662.550	447.036	324.350	252.993
β_3	N	3.948		1.258	
	S	3.975		1.278	
	E	3.953		1.270	
	W	3.997		1.163	
r^2		.994		.994	

Note: SM = Shade Management

TABLE 2

Regression Coefficients: Overhang Solar Correction Factor

		Electricity (Exponential)	Peak Demand (Exponential)	Peak Demand (Linear)
δ_1	N	.507	.725	-
	S	.534	.576	-
	E	.842	-	-.608
	W	.550	-	-.467
δ_2	N	-2.083	-1.271	-
	S	-1.708	-2.029	-
	E	-.893	-	-
	W	-1.396	-	-
r^2		.992	.991	.998

Note: east and west peak demand curves are linear.

TABLE 3

Regression Coefficients: Daylighting Lighting Correction Factor (SI Units)

ϕ_1	N	.754
	S	.753
	E	.758
	W	.756
ϕ_2	N	-.0000381
	S	-.0000429
	E	-.0000598
	W	-.0000710
ϕ_3	N	-16.325
	S	-16.720
	E	-21.728
	W	-20.003
ϕ_4	N	.0149
	S	.0152
	E	.0198
	W	.0179
r^2		.978

DISCUSSION

The above equations were used to predict the performance of the seven window glazing products shown in Table 4. Clear, tinted, and low-E single and double glazings were investigated. These products are currently commercially available and represent windows used in hot and humid locations and also systems that offer improvements in performance. The improvement is associated with changing proportions of total solar to visible transmittance, since these dominate the thermal variations due to window conductance differences.

Values for glazing luminous efficacy, k_e, range from 1.34 for low-E green-tinted double glazing with shading coefficient of 0.35 and visible transmittance of 0.47, to 0.69, for gray-tinted double pane with SC of 0.55 and τ_v of 0.38. Clear glazings with and without a low-E coating have the highest SCs and τ_vs and are most suitable for use with small window areas. Although green- and gray-tinted double glazings have similar SCs, their τ_vs differ greatly. Other tinted glazings, e.g., bronze, have τ_vs that are between green and gray. Adding a low-E coating decreases the shading coefficient more than the visible transmittance; thus green low-E double glazing is presented as a low-SC option with the highest τ_v. Although the low-emittance glazings are normally used in locations that require heating, this study indicates that they perform well in locations such as Singapore, particularly if combined with a spectrally selective glazing such as green glass.

Figure 2 shows the variation of the solar correction factor from overhangs for electric usage and peak demand as a function of the ratio (R) of projection width to window height. Generally, asymptotes are approached as the ratio increases; however, the peak demand curves for the east and west are more linear than exponential. This is because for these orientations, the peak occurs when the sun is low in the sky. The k_o values at $R = 0.6$, the maximum ratio used in our work, represent decreases of 30%-35% for annual electricity and 27%-40% in peak demand, depending on window orientation.

Figure 3 presents the lighting correction factor from daylighting for four orientations and three lighting levels (323, 538, and 753 lux [30, 50, 70 footcandles]) as a function of effective aperture. Annual lighting energy savings with daylighting drop linearly until the space begins to become saturated with daylight; savings then asymptotically approach the maximum of 69%-74%. Daylighting savings are greatest when the desired interior illuminance is lowest. For small effective apertures, there is approximately a 10%-15% variation due to orientation, with east giving the largest reduction of lighting energy and north/south the smallest. However, the orientation effect is small and becomes insignificant as the asymptote is approached.

We found that there was a very small change in daylight availability when using overhangs. This is probably due to the large fraction of diffuse solar radiation in Singapore. Figure 4 shows the change in k_d at a lighting level of 538 lux (50 footcandles) when shade management is employed. Throughout most of the effective aperture range, daylight was reduced by 20%-25% for eastern and western orientations and less than 10% for north and south.

Solar- and lighting-induced electric energy consumption and peak demand are presented in Figures 5 and 6 as a function of the product of shading coefficient and window area. These figures represent the form expressed by Equation 1 with the exception that glazing conductance, a very minimal effect, is ignored. The incremental increase from solar gain and the decrease in lighting from daylighting are shown. Results are for four orientations, at a relatively efficient lighting power density of 18.3 W/m^2 (1.7 W/ft^2), a lighting level of 538 lux (50 footcandles), with and without the largest overhang. Also annotated are the relative positions of the seven glazings for a window area of 50 m^2 (538 ft^2).

TABLE 4

Window System U-values and Shading Coefficients Analyzed

Window Type	Summer U-Value	Shading Coefficient (SC)	Visible Transmittance (τ_v)	Efficacy $k_e = \tau_v/SC$
(1) G	6.11 (1.07)	.95	.88	.93
(2) G_g	6.45 (1.13)	.72	.75	1.04
(3) G-G	3.31 (.58)	.82	.78	.95
(4) G_g-G	3.37 (.59)	.58	.66	1.14
(5) G_y-G	3.37 (.59)	.55	.38	.69
(6) GE-G	1.94 (.34)	.67	.74	1.10
(7) G_gE-G	1.83 (.32)	.35	.47	1.34

Notes:

1. U-value units are W/m^2C ($Btu/hr\text{-}ft^2F$).

2. G denotes glazing layer; G_g tinted green; G_y tinted grey;
   E, a sputtered low-E coating (e=.1 for clear, .07 for green).

3. Glass thickness is 6 mm (0.25 in); gap width between layers is 12.7 mm (0.5 in).

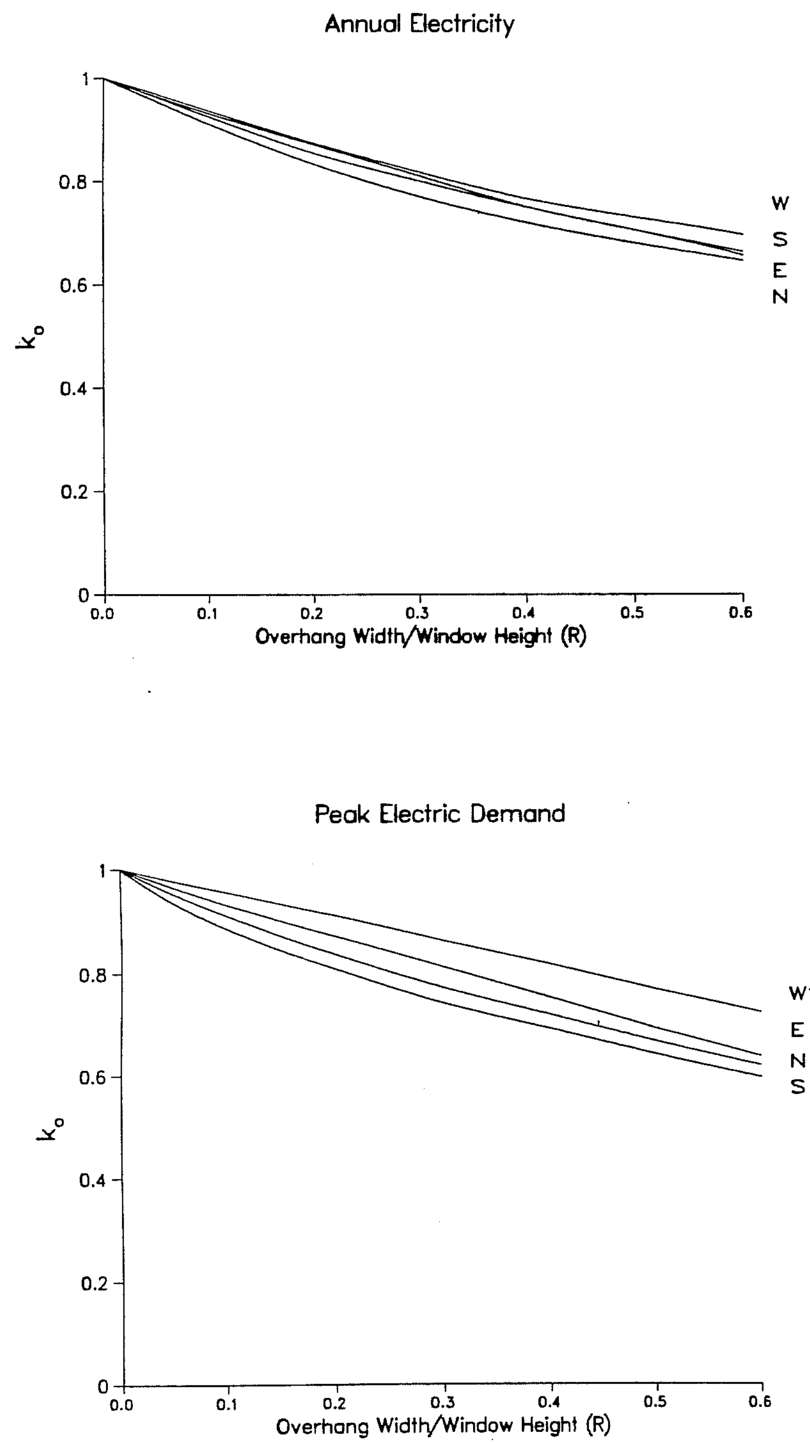

Figure 2. Solar correction factor for overhangs for perimeter zone annual electricity consumption and peak demand. The nondimensional factor for each orientation is the ratio of overhang width to window height .

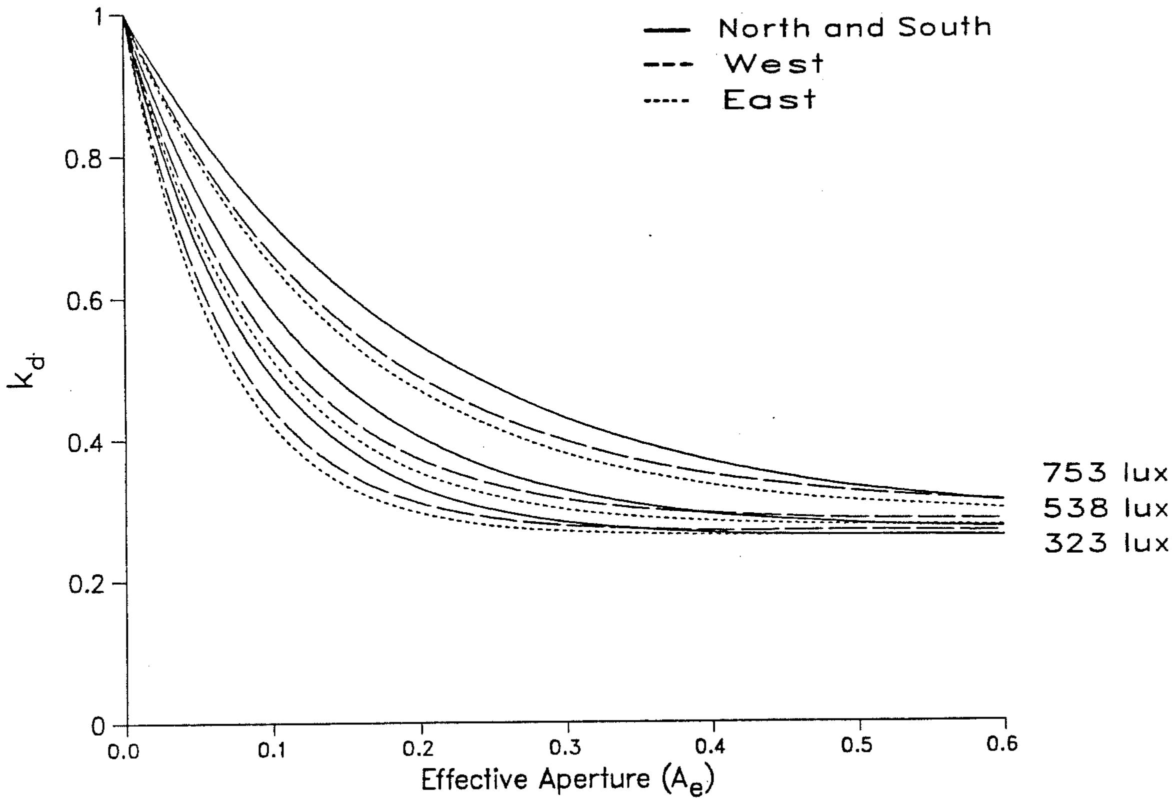

Figure 3. The daylighting correction factor, a nondimensional value, is a function of effective aperture at lighting levels of 753, 538, and 323 lux.

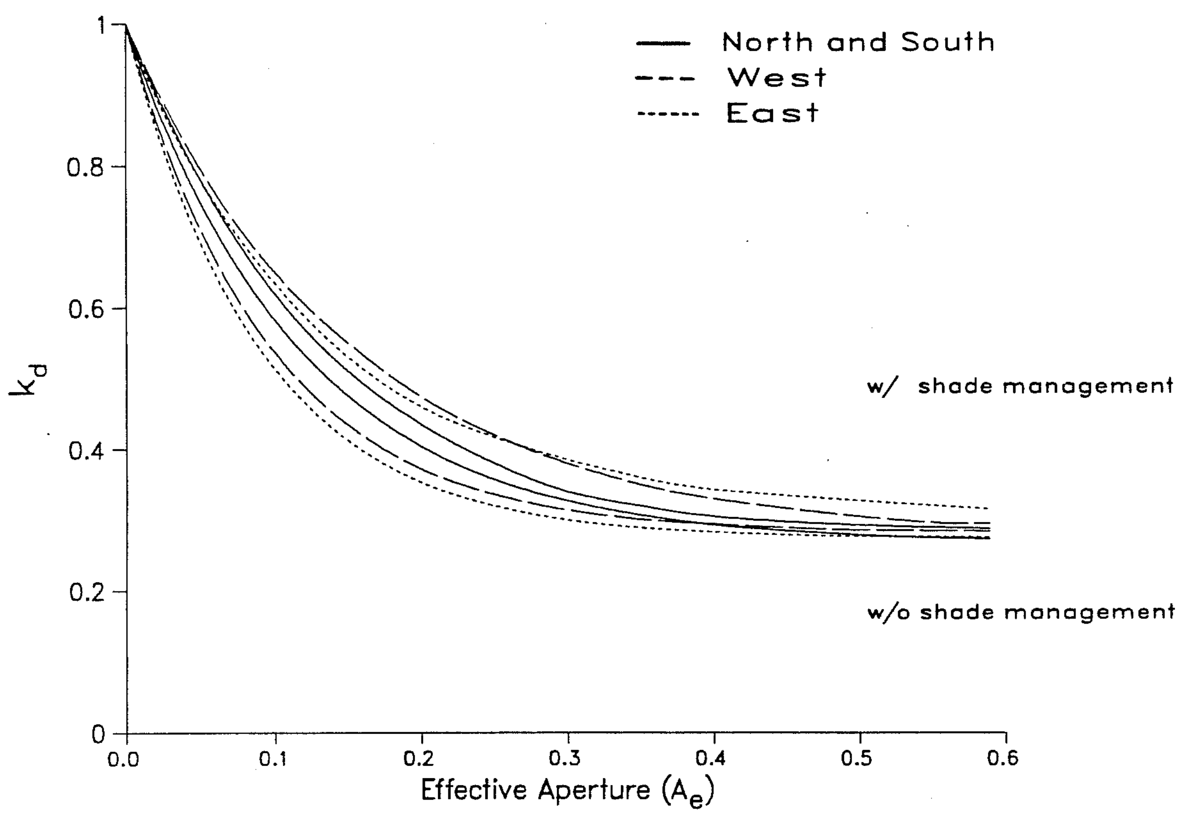

Figure 4. This plot shows the effect of shade management on the daylighting correction factor, a non-dimensional value, and a function of effective aperture at a lighting level of 538 lux.

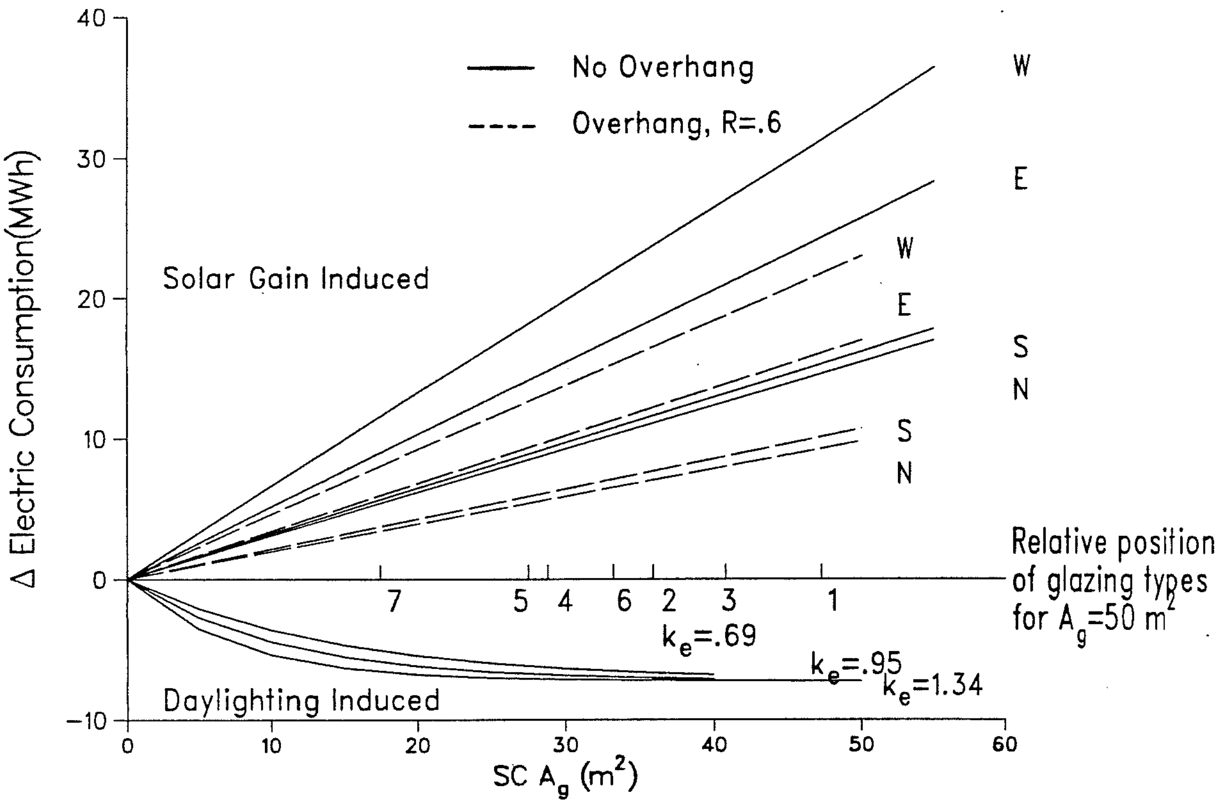

Figure 5. Incremental solar-gain and daylighting-induced electric energy usage for four orientations of a commercial building as a function of the product of shading coefficient and window area. The lighting power density is 18.3 W/m^2 and the interior lighting level is 538 lux. The seven glazing types (from Table 1) are plotted at an area of 50 m^2 for comparison. For east and west orientations, the data for overhangs are about the same as for shade management.

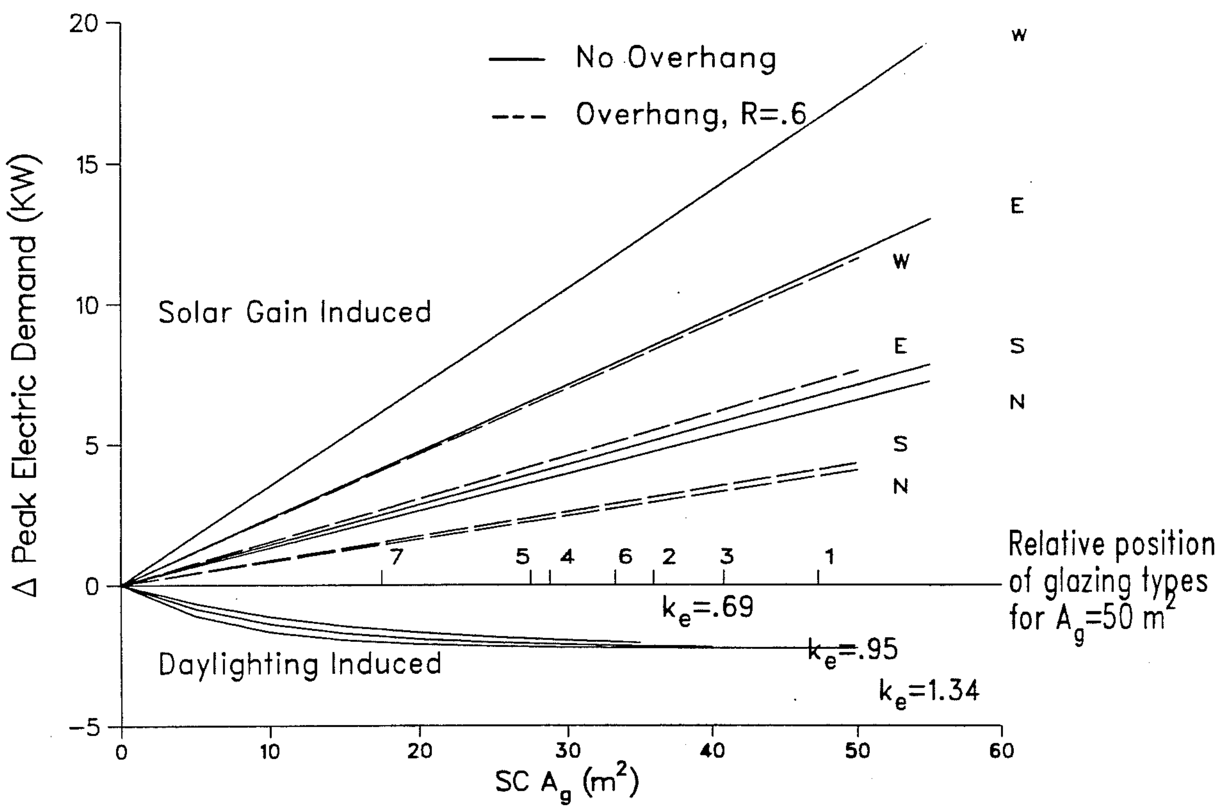

Figure 6. Incremental solar-gain- and daylighting-induced peak electric demand for four orientations of a commercial building as a function of the product of shading coefficient and window area. The lighting power density is 18.3 W/m^2 and the interior lighting level is 538 lux. The seven glazing types (from Table 1) are plotted at an area of 50 mm^2 for comparison. For east and west orientations, the data for overhangs are about the same as for shade management.

These curves demonstrate the importance of orientation. North and south receive very little direct-beam solar radiation and therefore yield the lowest solar gain increments. A western orientation requires twice as much electricity and demand as north and south, with east being between the two. Overhangs with $R = 0.6$ provide about 30%-35% reduction in solar gain on each orientation, and because the gain is greatest on the west, the absolute benefit of an overhang is greatest on the west. This is particularly important since overhangs can provide substantial benefits without significantly diminishing daylighting potential. On a western orientation, in particular, the daylighting benefit can be overwhelmed by solar gains. Thus, minimal effective apertures with overhangs are necessary to mitigate the substantial solar load.

Glazing type can also have a substantial impact on solar load reduction but may do so at the expense of daylighting. Table 5 shows the percent reduction in solar-gain-induced electric usage for each glazing when using single pane clear as a base. The solar values given can be used for both usage and demand and for all orientations, with and without overhangs, since the percent change in energy or demand shown along the vertical axis in Figures 5 and 6 is equivalent to the percent change in shading coefficient because of the linearity associated with Equation 1. The largest changes occur with low-E tinted double glazing. For the module used in this study, annual cooling energy due to solar gain can be reduced by 63% when using this glazing type. This corresponds to a net cooling energy reduction of 20 MWh and peak demand reduction of 10KW for a western orientation. The monolithic green absorbing glass unit results in a 23% reduction, so the addition of the low-E coating in the double glazed unit provides significant additional benefits.

In addition to the solar gain effects, Figures 5 and 6 also show some of the changes in daylighting savings. Lighting reduction curves are shown for an eastern orientation for three (two limiting and one midpoint) values of efficacy corresponding to glazings in Table 4 (types 3, 5, and 7). For electric energy consumption, the savings due to daylighting can approach the same magnitude as savings from the use of large overhangs. For the 50 m^2 window area, all glazing types have about the same daylight utilization, because the asymptotic values have been approached. One sees, however, that glazing type 7 (low-E green tinted), which has the lowest shading coefficient providing the maximum reduction in solar gain, also has the largest efficacy, k_e=1.34. Glazing type 3 ($k_e = 0.95$) provides almost the same available daylighting benefits as type 7 but with a large increase in solar gain. Better performance could be achieved by decreasing the glazing area to reduce the solar load without affecting daylight availability significantly.

Figures 5 and 6 also can be used for predicting the effects due to shade management. It was previously indicated that shade management was most useful for eastern and western orientations because of the large fraction of diffuse radiation present for north and south. The reduction in solar gain is coincidentally approximately the same as the decrease due to overhangs. Thus, for a shading coefficient multiplier of 0.6, about a 30% reduction is seen in both perimeter zone electricity use and peak demand. Note also that this shade management scheme has no effect on glazings with shading coefficients lower than 0.4. With such a low SC, the 63 W/m^2 (20 W/ft^2) direct solar radiation level for shade management is not reached. Using interior shades does influence the savings with daylighting. The lighting curves in Figures 3 and 4 remain exponential in form and the daylighting reduction is about 25%.

TABLE 5

Percent Reduction in Solar Induced Annual Electric Usage
With Single Pane Clear Glazing as a Base.

Window Type	Solar Gain %	Shading Coefficient
(1) G	0	.95
(2) G_g	23	.72
(3) G-G	13	.82
(4) G_g-G	40	.58
(5) G_y-G	42	.55
(6) GE-G	29	.67
(7) G_gE-G	63	.35

CONCLUSIONS

Many techniques are available for reducing the annual electricity requirements and peak electrical demands of commercial office buildings in hot and humid climates. Several methods that relate to the design of the fenestration system have been documented. The effects of building orientation, external and internal shading devices, and glazing selection have been briefly discussed. A comparative study of several different glazings and the solar-optical properties that contribute to energy efficient design have also been presented. Conclusions are as follows:

1. Controlling solar gains from windows should be a major consideration in any new building design in hot climates.
2. There is an extremely large variation in direct solar heat gain with orientation. Orientation also affects the level of influence that exterior and interior shading devices have on controlling these gains.
3. Lighting energy savings through the use of daylighting is a function of the visible transmittance of the glazing, the window area, desired lighting level, and lighting power density. It is possible to reduce electric lighting requirements by as much as 75% in perimeter zone offices.
4. Selecting the proper glazing type is as critical as orientation. It has been shown that it is possible to reduce electricity and peak demand of perimeter zones by using glazings with high efficacy values. These types of glazings reduce solar heat gain while maintaining a satisfactory level of daylighting utilization.
5. The use of exterior and interior shading devices on western and eastern orientations can reduce solar loads to the point that they are equivalent to northern and southern orientations. Shade management, as implemented in this study, gave results similar to an opaque overhang whose projection-width to window-height ratio was 0.6.
6. In Singapore, the use of overhangs did not significantly affect daylight availability because of the large fraction of diffuse sunlight. Interior shades, however, reduced daylight effectiveness 20%-25% for eastern and western orientations and less that 10% for north and south throughout most of the effective aperture range.
7. Previous studies (Arasteh 1985; Johnson 1986; Sweitzer 1987) indicate that it is possible to have large first-cost savings by using high-efficacy glazings with daylighting controls rather than conventional glazings. The lower chiller and HVAC system first costs will pay for some or all of the increased glazing, solar shading, and lighting-control costs in many cases.

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